Fig. 16 is a functional flow diagram of an apparatus embodying the present invention that compensates the consistency measurement of a consistency meter, in accordance with the present invention.

Figs. 17 - 19 are configurations for an apparatus in accordance with the present invention.

Figs. 20 - 22 are plots of the output of an apparatus embodying the present invention for compensating a microwave consistency meter, in accordance with the present invention.

Fig. 23 is a block diagram of a closed loop system having a microwave consistency meter compensated for entrained gas, in accordance with the present invention.

Fig. 24 is a block diagram of a closed loop system having an electromagnetic flow meter compensated for entrained gas, in accordance with the present invention.

Best Mode for Carrying Out the Invention

Referring to Fig. 1, an apparatus, generally shown as 10, is provided to measure volumetric flow rate and gas volume fraction in liquids and mixtures (e.g. paper and pulp slurries or other solid liquid mixtures) having entrained gas therein (including air). The apparatus 10 in accordance with the present invention determines the speed at which sound propagates within a pipe14 to measure entrained gas in liquids and/or mixtures 12. To simplify the explanation of the present invention the flow propagating through the pipe will be referred to as a mixture or slurry with the understanding that the flow may be a liquid or any other mixture having entrained gas therein.

The following approach may be used with any technique that measures the sound speed of a fluid. However, it is particularly synergistic with sonar based volumetric flow meters such as described in U.S Patent Application, Serial No. ~~(Cidra's Docket No. CC-0122A)~~ 10/007,736 and U.S. Patent Application, Serial No. 09/729,994 ~~(Cidra's Docket No. CC-0297)~~, filed December 4, 200, now US6,609,069, which are incorporated herein by reference, in that the sound speed measurement, and thus gas volume fraction measurement, can be accomplished using the same hardware as that required for the volumetric flow measurement. It should be noted, however, that the gas volume fraction measurement could be performed independently of a volumetric flow measurement, and would have utility as

- 6 -

as polarized fluoropolymer, polyvinylidene fluoride (PVDF). The piezoelectric film sensors are similar to that described in U.S. Patent Application Serial No. $\frac{10/712,833}{\text{(CiDRA Docket No. CC-0676)}}$, which is incorporated herein by reference.

The apparatus 10 of the present invention may be configured and programmed to measure and process the detected unsteady pressures $P_1(t) - P_N(t)$ created by acoustic waves and/or vortical disturbances, respectively, propagating through the mixture to determine the SOS within the pipe 14 and the velocity of the mixture 12. One such apparatus 110 is shown in Fig. 4 that measures the speed of sound (SOS) of one-dimensional sound waves propagating through the mixture to determine the gas volume fraction of the mixture. It is known that sound propagates through various mediums at various speeds in such fields as SONAR and RADAR fields. The speed of sound propagating through the pipe and mixture 12 may be determined using a number of known techniques, such as those set forth in U.S. Patent Application Serial No. 09/344,094, entitled "Fluid Parameter Measurement in Pipes Using Acoustic Pressures", filed June 25, 1999, now US 6,354,147; U.S. Patent Application Serial No. 09/729,994, filed December 4, 2002, now US 6,609,069; U.S. Patent Application Serial No. 09/997,221, filed November 28, 2001, now US 6,587,798; and U.S. Patent Application Serial No. 10/007,749, entitled "Fluid Parameter Measurement in Pipes Using Acoustic Pressures", filed November 7, 2001, each of which are incorporated herein by reference.

In accordance with the present invention, the speed of sound propagating through the mixture 12 is measured by passively listening to the flow with an array of unsteady pressure sensors to determine the speed at which one-dimensional compression waves propagate through the mixture 12 contained within the pipe 14.

As shown in Fig. 4, an apparatus 110 measuring the speed of sound in the mixture 12 has an array of at least two acoustic pressure sensors 115,116, located at two locations x_1, x_2 axially along the pipe 14. One will appreciate that the sensor array may include more than two pressure sensors as depicted by pressure sensors 117,118 at location $,x_3, x_N$. The pressure generated by the acoustic waves may be measured through pressure sensors 115 - 118. The pressure sensors 15 - 18 provide pressure time-varying signals $P_1(t),P_2(t),P_3(t),P_N(t)$ on lines 120,121,122,123 to a signal processing unit 130 to known Fast Fourier Transform (FFT) logics 126,127,128,129, respectively. The FFT logics 126 - 129

- 10 -

This indicates that an entrained air measurement could be accurately performed, within 0.01% or so, with little or no knowledge of the consistency of the slurry. The chart does show a strong dependence on line pressure. Physically, this effect is linked to the compressibility of the air, and thus, this indicates that reasonable estimates of line pressure

5 and temperature would be required to accurately interpret mixture sound speed in terms of entrained air gas volume fraction.

Fig. 7 also shows that for the region of interest, from roughly 1% entrained air to roughly 5% entrained air, mixture sound speeds (amix) are quite low compare to the liquid-only sound speeds. In this example, the sound speed of the pure water and the 5% pulp

10 slurry were calculated, based on reasonable estimates of the constituent densities and compressibilities, to be 1524 m/s and 1541 m/s, respectively. The sound speed of these mixtures with 1% to 5% entrained air at typical operating pressure (1atm to 4 atms) are on the order of 100 m/sec. The implication of these low sound speed is that the mixture sound speed could be accurately determined with a array of sensors, ie using the methodology

15 described in aforementioned U.S Patent Applications, Serial No. ~~(Cidra's Docket No. CC-0066A)~~ [09/344,094], and/or Serial No. ~~(Cidra's Docket No. CC-0066B)~~ [10/007,749], with an aperture that is similar, or identical, to an array of sensors that would be suitable to determine the convection velocity, using the methodology described in aforementioned U.S Patent Application, Serial No. ~~(Cidra's Docket No. CC-0122A)~~ [10/007,736], which is incorporated herein by reference. Thus,

20 performing a volumetric flow measurement and an entrained air volumetric flow measurement using the convection velocity and mixture sound speed simultaneously, with the same sensor array would provide functionality currently unavailable to the paper and pulp industry.

For the sound speed measurement, the apparatus 110 utilizes similar processing

25 algorithms as those employed for the volumetric flow measurement. As with convective disturbances (which is described in greater detail hereinafter), the temporal and spatial frequency content of sound propagating within the process piping is related through a dispersion relationship.

$$k = \frac{\omega}{a_{mix}}$$

- 17 -

VDC, 2 to 20 mA constant-current supply. A data acquisition system of the present invention may incorporate constant-current power for directly powering integrated circuit piezoelectric sensors.

5   Most piezoelectric pressure sensors are constructed with either compression mode quartz crystals preloaded in a rigid housing, or unconstrained tourmaline crystals. These designs give the sensors microsecond response times and resonant frequencies in the hundreds of kHz, with minimal overshoot or ringing. Small diaphragm diameters ensure spatial resolution of narrow shock waves.

The output characteristic of piezoelectric pressure sensor systems is that of an AC-
10   coupled system, where repetitive signals decay until there is an equal area above and below the original base line. As magnitude levels of the monitored event fluctuate, the output remains stabilized around the base line with the positive and negative areas of the curve remaining equal.

It is also within the scope of the present invention that any strain sensing technique
15   may be used to measure the variations in strain in the pipe, such as highly sensitive piezoelectric, electronic or electric, strain gages and piezo-resistive strain gages attached to the pipe 12. Other strain gages include resistive foil type gages having a race track configuration similar to that disclosed U.S. Patent Application Serial No. 09/344,094, filed June 25, 1999, now US 6,354,147, which is incorporated herein by reference. The
20   invention also contemplates strain gages being disposed about a predetermined portion of the circumference of pipe 12. The axial placement of and separation distance ΔX_1, ΔX_2 between the strain sensors are determined as described herein above.

It is also within the scope of the present invention that any other strain sensing technique may be used to measure the variations in strain in the tube, such as highly
25   sensitive piezoelectric, electronic or electric, strain gages attached to or embedded in the tube 14.

The present invention also contemplates the sensors 18-21 may be ultra-sonic sensors, especially, for measuring the vortical disturbances to determine the velocity of the flow, similar to that described in U.S. Patent Application No. 10/756,977 (Cidra Docket No. CC-0700),
30   filed on January 13, 2004, which is incorporated herein by reference.

- 29 -